SIM Report No. 9

Scientific Investigations in Micronesia
1949-

The Hydrology of Arno Atoll, Marshall Ids.

by Doak C. Cox

Pacific Science Board
National Research Council
N7-onr-291: T O IV & Viking Fund Inc.

SCIENTIFIC INVESTIGATIONS IN MICRONESIA

operates with financial assistance from
Contract N7-onr-291, Task Order IV
between

THE OFFICE OF NAVAL RESEARCH

and

THE NATIONAL ACADEMY OF SCIENCES

SIM has developed as a successor to the former CIMA project with an enlarged scope that includes field research in the physical, biological, and life sciences. Field work under SIM has been conducted in Guam, American Samoa, and in the islands of the Trust Territory in Micronesia since 1949 with transportation and facilities contributed by the Department of the Navy. The field research has been carried out in cooperation with universities, museums, research institutions, and Government agencies under this project of the Pacific Science Board of the National Research Council, supported by the Office of Naval Research and aided by financial assistance from the Viking Fund and other private sources.

THE HYDROLOGY OF ARNO ATOLL,

MARSHALL ISLANDS

SCIENTIFIC INVESTIGATIONS IN MICRONESIA

Pacific Science Board

National Research Council

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Honolulu, Hawaii
March 1951

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ACKNOWLEDGEMENTS

The author of this report participated in the 1950 SIM (Scientific Investigation of Micronesia) Project of the Pacific Science Board of the National Research Council, and the report is based on his field work on Arno from July 8 to August 5, 1950. This project was supported by funds granted to the National Academy of Sciences by the Office of Naval Research, and the field work was carried out with the active assistance of the Navy Department, the Military Air Transport Service and the officials of the Civil Administrative Staff of the Trust Territory (Navy). Particularly to the latter officials, too numerous to list individually, the author is indebted for assistance in obtaining and transporting equipment used in the work and for providing climatic data for Majuro. Miss Ernestine Akers, Honolulu Secretary of the Pacific Science Board assisted greatly and has shown more than official interest in the study.

The author's participation was possible because of a leave granted from his regular duties at the Experiment Station of Hawaiian Sugar Planter's Association. For the opportunity thus provided to join the project he is very grateful. Dennis Lee, of the Experiment Station, has assisted with the preparation of the accompanying ground-water diagram.

Several government agencies furnished special equipment that was invaluable in the study. Tide gaging equipment was loaned by the U. S. Coast and Geodetic Survey, and the Survey has worked up the basic tidal data. The U. S. Weather Bureau loaned the meteorological equipment, and the U. S. Geological Survey loaned a water-stage recorder.

The author is indebted to the other members of the Arno group who assisted in the collection of data, particularly to Gerald Wade who was

in principal charge of the meteorological work, and to the interpreters, especially Konto and William who helped make surveys and dig wells as well as provide information and interpret the information of others. Finally, thanks are due to Jokon, the scribe at Ine, who has been continuing certain meteorological and hydrologic measurements since the partyleft, and to John Tobin who has been forwarding these data with comparative data from Majuro.

HYDROLOGY OF ARNO ATOLL

CLIMATE

The field investigation of the climate of Arno consisted of daily measurements of rainfall, maximum and minimum temperature, and humidity, and continuous recording of temperature and humidity. The principal weather station was at Ine Village on Ine Island on the south side of the atoll. Irregular rainfall measurements were also made on Bikarij Island and Arno Island. Due to shipping difficulties receipt of the meteorological equipment was delayed, and measurements were not started until July 2. All measurements were continued until the first week in September when the last of the party left Arno. Most of the records, therefore, cover a period of not quite two months. The Ine raingage was left in place, however, and Jokon, the scribe at Ine Village agreed to continue the daily measurements, sending the results monthly to Honolulu. As required, he will be assisted by William, the Ine school teacher.

The various measurements made so far constitute, by themselves, a hopelessly incomplete record of the Arno climate. The shorter periods of measurement will not indicate the changes even through a single seasonal cycle, and even a year's measurement of rainfall will give no indication of the limits of annual variation. However, they may be correlated with fragmentary but longer term records on the neighboring island of Majuro and with other records for Marshall Is., so that rough but useable definition of at least the hydrologic factors in the climate of Arno may be obtained.

The rainfall measurements recorded from July through November at Ine are tabulated in the appendix. The mean monthly rainfall has been 17 inches, equivalent to an annual rainfall of over 200 inches. As the record includes more summer months than winter months and as winter is reported to be the dry season, the actual annual rainfall will probably be somewhat less.

During the same period a mean monthly rainfall of 20 inches was recorded at Majuro. Most of the rainstorms are of small diameter, perhaps 10 miles across at the most. It is to be expected, therefore, that short period measurements at stations 10 miles or more away from each should show very poor correlation. Longer period totals, however, in which the effects of individual rainstorms are less important, should show greater correlation reflecting the movements of large air masses. The difference between the Ine rainfall and that of Arno, therefore, may well be a significant one. A long term estimate of the mean rainfall of Arno can probably be made when more complete records for Majuro and other Marshall Is. records become available and have been analyzed.

During a 24-day period the rainfall on Arno Island totalled 14 inches. The total for Ine for the same period was 16 inches and that at Majuro was 18 inches. This is interesting because the Arno station lies roughly between the Ine and Majuro stations yet its rainfall is not intermediate between that at Ine and Majuro but lower than either. The difference for the short period may, however, not be significant. Only four days rainfall in July were recorded at Bikarij. Afterwards the gage could not be visited until just before the party left Arno, when

it was found to be overflowing. As the total rainfall in the interim had been nearly 30 inches at Ine the overflow was to be expected, and the record contributes very little.

Daily rainfall during the period ranged from nil to over 4.14 inches. Most of this rain came in sudden intense rainstorms. No relation of rainstorm frequency to time of day was noted.

The temperature during the period of operation of the weather station ranged from 73° to 90° F. with a maximum daily range of 19° and a common daily range of 10° to 12°. The morning humidity readings ranged from 78% to 100%. The hydrothermograph records have not been analyzed, but casual inspection shows that the humidity usually dropped during the daytime, and that the humidity was generally between 80% and 95%.

TIDES

The tides of Arno were studied in some detail because of the importance of the elevation of the water table of the fresh ground-water bodies of the islands above mean sea level, and because of the importance of the tidal fluctuations in the fresh ground-water bodies of the islands. The shipping delay resulted in the loss of valuable recording time in this study also. One tide gage was established on the ocean side of Ine in the second week in July and a second was established on the lagoon side in the last week in July. The gages were kept in operation until just before the party left.

An analysis of the tide records by the Coast and Geodetic Survey indicates that the mean tide range in the ocean is 3.8 feet and the spring range is about 4.1 feet. The mean water level in the lagoon is

about the same as that in the ocean, but the mean tide range is 0.1 feet greater than that in the ocean. The explanation for this increase in tide range in the lagoon is not known.

A number of bench marks were established to facilitate leveling between tide gages and wells. Their description and elevations are listed in the appendix.

RAIN CATCHMENT

There is no runoff of the rainfall from the Island of Arno. At the most the water may run a few tens of feet on the packed surface of the main trails. Most of the rainfall seeps very quickly into the highly permeable soil. Artificial surface catchment of rainfall is, however, very important. It furnishes the entire supply of water for cooking and drinking in Ine and Arno villages and by far the major supply for those purposes generally. The best catchment structures are corregated iron roofs. In Ine Village perhaps half of the houses have such roofs, totalling about 12,000 horizontal square feet of catchment surface. Of this surface not quite 6,000 square feet is actually used, the water being led by troughs to concrete cisterns or discarded oil drums. In Ine Village there are 22 cisterns totalling about 69,000 gallons storage volume. Of these, however, only 17, totalling 53,000 gallon capacity are actually in use. With the barrels the total water storage capacity in the village is about 54,000 gallons. This is the equivalent of nearly 150 inches of rain on the tributary catchment areas. However, the ratio of the catchment areas to the capacities of the cisterns and barrels they feed is extremely variable. On the one hand some cisterns are fed only by the

roofs that cover them, and on the other some large roofs feed one or two drums. Domestic water shortages, reported recurrent during dry seasons, could probably be completely avoided if existing catchment areas were all connected with nearby existing cisterns in such a manner that the ratios of cistern volumes and repective tributary catchment areas should be as nearly a uniform as possible.

In the outlying districts the crowns of pandanus and coconut trees are used as rain catchments, the water being led by way of a prop root or a stick from the trunks of the trees, down which it runs after being concentrated by the funnels of the upper whorls of leaves, to an oil drum. Nearly every house or small group of houses that does not have a cistern on Ine and Arno Islands has one tree rigged for a rain catchment.

The rain water contained 8 to 9 parts per million chlorides at Ine during July and August. This small quantity is undoubtedly due to the solution by the rain of salt crystals resulting from evaporation of sea spray. At times of low rainfall the salinity of the rainwater may increase somewhat. It is probably higher on the windward islands than on Ine.

GROUND-WATER

The groundwater observations made on Arno can be intelligently discussed only if they are considered in relation to the shallow geological structure, and can be understood only when some of the principles of ground-water occurrence as they relate to atoll islands are known. There follows, therefore, first a discussion of shallow geological structure, second a theoretical discussion of principles of ground-water occurrence

in atolls, and third the discussion of the Arno observations as a confirmation, evaluation and expansion of the principles.

Notes on geology pertinent to ground-water occurrence

The islands on an atoll are mere heaps of sand and boulders on the "reef platform", the top of the reef that characterizes the atoll. Their position and the character of the materials within them are determined by shape, size, and exposure of the sections of the reefs on which they are developed. J. W. Wells' report on the Coral Reefs of Arno Atoll describes (p. 4) the boulder ramparts characteristically surmounting the beaches on the ocean sides of the islands. The ocean beaches themselves, though not composed entirely of boulders like the rampart, contain a large proportion of boulders and cobbles and very little fine sand. The lagoon beaches, on the south side of the lagoon at least, are composed principally of sand, much of it very fine. Because the islands are the result of accretion of beach materials, generally on both shores, the materials appearing on the beaches on the two shores of the islands should be representative of the materials composing the islands as a whole. The permeability of the coarse ocean-beach sediments should expectably be much higher than that of the fine lagoon-beach sediments.

Wells also describes the beach rock commonly exposed along the shores. In this material, whether derived from sand or beach gravel, the original pores ~~and~~ are very largely filled with cement so that the permeability is very low.

The small dashed lines in diagrams A and E of the accompanying figure indicate the depths at which gravel and hard rock were encountered under the sand as indicated by wells along two profiles across Ine Island. The

lower small dashed-line represents the top of well consolidated rock, either as seen in the bottom of large wells, as exposed on the surface, or as estimated from the limit to which drivepoints could be simply churned down, or the top of gravel exposed in wells or on the surface. The long dashed line represents a projection of the reef surface beneath the islands.

It will be noted that under the narrow part of the island shown in diagram A, there is no consolidated rock above the level of reef platform except on the lagoon beach where there is beach rock. This section was drawn across a canoe portage where a channel had been washed out across the island in a hurricane. The beach rock extended on surface only to the west edge of the portage and was found by probing to extend only part way across the portage, so that a few feet east of the section shown there was no beach rock. The whole section of the island except for the face of the lagoon beach and a small lagoon beach ridge or dune were composed of coarse sand and gravel.

In the wider part of the island there is apparently hard rock to two or three feet above the level of the reefs but not above mean sea level except where beach rock was formed on the ocean beach. This hard rock might represent merely boulders too large to crack with the drivepipe under most of the wells, but it was evidently a continuous layer under well B. No beach rock was exposed on the lagoon beach at this section, and there is room for only a very narrow beach rock zone at the most between the beach surface and well P.

The structure and texture are not so obvious in the underlying reef are as in the overlying sediments. It will be noted in Wells' discussion

of reef zonation (pp. 11-16) that along the south side of Arno Atoll the lagoon reefs are covered with extensive patches of sand that are absent or at least not prominent on the ocean reef. Whether the surface conditions are typical of the underlying materials depends on whether the present environments are typical of those prevailing while the reefs were being built. Unfortunately our knowledge of the history of coral reefs is so slight that there is no general agreement as to the conditions of their development. All that can be said, therefore, is that there appears to be a possibility for the development of asymmetry in the permeability of the reef itself. As will be shown in the analysis of the ground-water measurements such asymmetry apparently obtains under Ine Island.

Principles of ground-water occurrence on atoll islands

Most of the rainfall on atoll islands, all that is not caught on and evaporated from the plants and the surface of the ground, seeps quickly into the ground. A part of this seepage is held in capillary openings in the soil and remains available to shallow-rooted plants. In most regions of the world this soil water is the most important source of water for plants, which withdraw it and transpire it to the atmosphere. It is undoubtedly a very important source on atoll islands and probably the main source for many plants, but the low ground elevations probably permit other plants to obtain water also from a deeper accumulation to be discussed.

The excess beyond the capillary capacity of the soil generally filters down through the sand to a foot or so above sea level, where it joins and maintains a body of more or less fresh water saturating the

rock and sand. From this body of what may be called basal ground-water it may be lost by withdrawal and transpiration by deep-rooted plants, by withdrawal from wells, and by underground flow laterally to the shorelines, both ocean and lagoon.

Salt water is denser than fresh water. Providing a volume of fresh water is somehow confined so that it cannot mix with the salt water, it will float on salt water, displacing the salt water just as a lump of ice or a stick would. The densities of fresh water and ocean water of usual salinity are such that approximately one unit of fresh water above the ocean water level will be supported by every 40 units below. A porous rock, partly submerged in ocean water, though it does not absolutely confine the water that saturates it, provides a restriction of flow that may reduce mixing sufficiently so that if fresh water is introduced into it, an integral body of fresh water will be maintained, floating on the salt water in the rock with its surface 1 foot above the level of the salt water for approximately every 40 feet of depth of fresh water below the salt water level. This principle, known as the Ghyben-Herzberg law after its first discoverers, applies in coastal areas, including islands, underlain by porous rocks in many parts of the world. Fresh water introduced by rainfall forms a basal fresh-ground-water layer whose depth below sea level is approximately 40 times the head or elevation of its water table above sea level.

It is a well established principle, called Darcy's law, first that the amount of ground water flowing through a sand of given cross section will be proportional to the hydraulic gradient, which, in a ground-water

body with a water-table that is not too steep, may be measured by the loss in elevation of the water table per unit distance measured in the direction of flow, and second that with the same hydraulic gradient in the same system but with sands of different sizes and degrees of compaction the amount of water flowing through a given cross section will be proportional to a factor called the permeability of the sand, which may be thought of as merely its capacity to transmit the water. Doubling the cross-sectional area, doubling the hydraulic gradient, or doubling the permeability of a system will double the rate of flow of water through it.

Disregarding the water withdrawn from wells, negligible on most atoll islands, the excess of rainwater introduced into a basal ground-water body of the Ghyben-Herzberg type over the amount of water withdrawn by plants from the body can be lost from the body only by flow to its margins at the shores. This flow can be induced only by a hydraulic gradient toward the shores, and by the Ghyben-Herzberg law the higher heads inland must be balanced by greater depths of fresh water inland. Assume for a moment that the permeability is constant and the rainfall, or rather its excess over transpiration and evaporation, is uniform both in space and time. Through the shore edges of the fresh water body all of the rainfall excess over the whole island must be flowing. Yet the head is low near the shore, and the thickness of fresh water small. By Darcy's law, the combination of high rate of flow and small cross sectional area must be balanced by a high shoreward hydraulic gradient, and rapid increase of both head and depth of fresh water inland. In sections of the island nearer to the center the head and depth of fresh water are

greater, and the amount of rainfall excess, being the part derived from the central part of the island only, is less. The hydraulic gradient must be smaller, and the rate of increase of head and fresh-water thickness inland is smaller. The fresh-water body, therefore, has a lenticular shape with a bow-shaped water table that is convex upward and with a lower, salt-water contact that is similarly but exaggeratedly convex downward.

In any island of uniform permeability the maximum head and thickness of fresh water will be greater if the rainfall is greater, smaller if the rainfall is less. If the rainfall is not uniform but varies seasonally there will be a seasonal change in the head and thickness of fresh water. Even the effects of daily variation in rainfall may cause variation in the head, although the effects of short term variations will lag behind the original variations and are not as great as the effects of long term variations of the same amount. The lag and damping are even greater in variations in the depth of fresh water than in variations in head.

In two islands of the same size and rainfall, the one with the lower permeability will have the higher head and the thicker fresh-water lens. In two islands of dissimilar size but having the same permeability and receiving the same rainfall, the larger island will have the higher head and the thicker fresh-water lens. Because of the change in shapes of the fresh water lens with change in size, the relationships of rainfall rate, island size, and permeability to the thickness of the fresh water lens are complicated and not those of direct proportionality.

The sea level, which controls the position of the fresh-water lens, is, of course, not constant but has tides. The loss of water from the

fresh ground-water lens is, therefore, controlled not by a constant base level but by a variable one; the hydraulic gradients throughout the lens and the rate of loss are, therefore, variable. As a consequence, the altitude of the ground-water table itself is variable, showing a tidal fluctuation much like the oceans but smaller and with a time lag. The lag and the degree of damping of the tide in the fresh water body are dependent on the distance from the coast, the permeability and depth of the aquifer, and the porosity of the section alternately saturated and drained. The greater the distance, the smaller the permeability and depth of aquifer, and the greater the porosity, the greater are the tidal damping and lag.

Fresh water resting upon salt water in the open will, of course, quickly mingle with the salt by diffusion and by mixing through turbulence accompanying any wave motion. In the medium of a permeable rock the rate of mingling is greatly reduced. Diffusion becomes an unimportant process, and there is no ordinary wave motion except at the extreme margins of the lens. However, the tidal movement of the lens and the alternate swelling and shrinking of the lens by increases and decreases in the rate of recharge, as compared to loss by withdrawals by plants and flow to the sea, result in raising and lowering of the salt-fresh contact. As the contact is raised, some fresh water is left in the rocks below the contact to mingle with the invading salt water, and as the contact is lowered some salt water is left above to mingle with the fresh. Consequently, the contact is not a sharp one but a gradual transition.

Where the spread of salt water into the fresh-water zone is larger than the downward component of the movement of the fresh water in response to recharge, the zone of mixture will extend clear to the top of the lens,

and if the rate of mixing is large enough or the recharge small enough, the water even at the top of the lens may be too brackish for drinking, or even for utilization by most plants. Sea water contains roughly 2 per cent chloride ions (equivalent to about 0.2% NaCl). Drinking water should preferably contain no more than 0.03 per cent chlorides and certainly no more than 0.1 per cent, or one twentieth the amount in sea water. The rate of movement of salt into and up through the fresh-water zone is dependent on the amount of climatic and tidal fluctuation of the theoretical salt water-fresh water boundary, on the vertical salt-content gradient, on the nature of the porosity (the mixing effect probably being heightened in material of variable pore size), and on the vertical component of the salt-content gradient (the transfer of salt being most rapid where the change in salt content with depth is highest). At the center of an island the tidal fluctuation is at a minimum, and the depth of fresh water is at a maximum, so that the rate of salt transfer is at a minimum, and there may be a low salt content and comparatively little change of salt content with depth near the top of the Ghyben-Herzberg lens. Near the coast the tidal range is greater in the ground-water body, and the total depth of fresh water is less, so that the salt gradient is steeper and the freshest water more brackish. At the shore the tide range is at a maximum and the depth of fresh water is at a minimum. Furthermore, at high tide there is a reverse hydraulic gradient carrying salt water into the island. Consequently all of the water emerging at the shore is brackish, and the change in salt content with depth and time is complex.

The average salinity at any point in a Ghyben-Herzberg lens in a small island is, therefore, complexed controlled by the size of the island,

the horizontal location of the point on it with reference to the coast lines and the vertical location of the point in the lens, by the average recharge (that is the average excess of rainfall over transpiration and evaporation losses) and by the variability of the recharge, by the permeability and porosity of the rocks, and by the tidal range in the surrounding water. The salinity at the point may be at a particular time greatly different from the average salinity at the point. Near the surface of the lens, except at the shore, the salinity will depend principally on the time elapsed since the last rainfalls and the magnitudes of those rainfalls in relation to the porosity and permeability. Soon after a rain the salinity will drop fairly quickly and then return gradually to a normal value which will be determined, like the salinity deeper in the lens, principally by seasonal changes of recharge, again with relation to the permeability. As has been already indicated, the salinity at the shore will be greatly influenced by the tides.

In the discussion so far, the rocks of the island have been assumed to have uniform permeability. That this assumption is unrealistic has been shown for Ine Island in the preceeding section, and the consequences of some of the expectable variability of permeability will be discussed here.

The difference in origin and texture between the reef problem and the islands on top of it constitutes perhaps the major source of a possible difference in permeability, but the permeability of each is highly variable, and no offhand guess can be made as to which has the larger overall permeability. If, on the other hand, the reef platform has a considerably lower permeability than that of the sediments of the overlying island, the

Ghyben-Herzberg principle might apply so far as the depth of the fresh-water lens, but the part of the fresh-water body in the island sediments would function very nearly as if it were an independent body on an impermeable layer. The tidal response would be considerably less than if the reef platform had equal permeability, but the fluctuations of head with variations in rainfall would be much greater. There would be much less opportunity for mixing, and the ground-water would be much fresher. If, on the other hand, the reef platform were much more permeable than the island sediments the system would function very much as if it were uniformly as permeable as the reef platform.

The predominance of boulders, cobbles, and coarse sand in the ocean beach and the predominance of fine sand in the lagoon beach suggest strongly a greater permeability in the oceanward parts of the Ine Island than in the lagoonward parts. This difference may apply in other islands. The difference in wave intensity on the two sides of the reef may result in making one side of the reef platform more permeable than the other. The effects of asymmetry in the permeability of the reef platform should be much more important than those of asymmetry in the permeability of the overlying sediments. Any asymmetry in the distribution of permeabilities would result in a lower water table, a thinner fresh-water layer, a greater tidal effect, and a greater salinity on the high permeability side than on the low permeability side.

The beach rock found on both ocean and lagoon shores is much less permeable than the uncemented sediments. Where there is beach rock at the shore, either on the surface or buried under new sand, it should serve as a barrier to outflow of the fresh water. If the reef platform is permeable

the effect of this barrier should be small, but if the reef platform is impermeable the beach-rock barriers might serve almost like the sides of a tank, effectively sealing off the fresh water from the ocean and causing a high head, very little tidal effect, and low salinity.

Beach rock related to old shore lines and buried now in interior parts of the islands might make similar barriers within the islands resulting in the separation of two or more independent fresh-water bodies if the reef platform were impermeable. Such layers of beach rock might also result in the perching of thin bodies of fresh water above sea level.

Ground-water observations on Arno

The accompanying diagrams summarize the most important part of the observations on ground-water conditions on Ine Island. The ground-water conditions are shown across the island at a point east of Ine Village where it is nearly 1400 feet wide and at a point west of Ine Village where it is only a little more than 300 feet wide. The conditions can best be discussed as they confirm, evaluate and expand the previously discussed principles of ground water occurrence.

The relationship between the head and the distance from the shorelines is shown by diagram A, a cross-section of the wide part of the island with a great vertical exaggeration. Three water-table positions are shown, the upper and lower being the tidal limits of the water table and the middle one being the mean position. Each slopes continuously toward the shorelines from a high point about a third of the way from the lagoon to the ocean shore, except where high-tide water table slopes inland for a short distance at each shore and also slopes toward the lagoon for a short distance near the center of the island. The probable

explanation for these deviations will be discussed shortly. The variation in mean head with distance from shorelines is shown with still greater vertical exaggeration by the two solid lines in diagram C. The heavier of these lines shows elevations of the mean water table for one day above long-term mean sea level. The lighter line indicates elevations of the mean water table for the same day above the mean sea level for that day. The latter line is probably more directly meaningful, because the heads may be expected to be very largely adjusted to tides of periods longer than a day.

Diagrams E and G indicate that the head at the center of the narrower part of the island is less than the head in the wide part of the island shown in diagrams A and C. Diagrams E and G do not show well the shape of the water table because there was only one measuring point in the narrow section of the island.

Diagrams B and F indicate the undistorted theoretical shapes of the Ghyben-Herzberg lenses in the cross sections of the wide and narrow parts of the island respectively. The depths of the lenses have merely been computed from the heads above mean sea level for the day on which they were measured, assuming that the heads were fully adjusted to long period tides. The lower limits shown may be regarded as the approximate levels of water half as saline as ocean water. Much of the water above these levels is too salty for humans or even plants to use.

That there is a greater effective permeability on the ocean side of at least the wide part of the island is indicated definitely by the relatively low head inland from the ocean shore and relatively high head inland from the lagoon shore as shown in diagrams A and C. The same asymmetry

in permeability probably exists in the narrow section too, but cannot be proved with only the one central measuring station.

The difference in permeability is also indicated by the greater damping and lag of the tides as they move in from the lagoon shore than as the move in from the ocean shore. In the tidal graphs, diagrams D and H, the damping and lag of the two principal tidal components, semi-diurnal and diurnal, are shown separately. Consideration of the tide as a whole would result in confusion, because the periods of the components are effective as well as the characteristics of the aquifer in determining the damping and lag, and the two components do not, therefore, behave as a unit as they move into the aquifer. The quantity a/x is a parameter describing the tidal progression as a whole and the values plotted were averaged from values obtained from both phase lag and damping effects in both semi-diurnal and diurnal components.

Attention has already been called to the landward slopes of the near-shore parts of the water table at high tide. Such a reversal of slope is expectable in most Ghyben-Herzberg lenses discharging without restraint to the sea. Because of the large range of the tide at Ine as compared to the maximum head the ocean and lagoon levels are actually nearly three feet higher than the highest part of the ground-water table at high tide. Because of the lag in the inland progression of the tide, the two lines representing the high-. and low-tide limits of the water table do not represent two respectively contemporaneous positions of the water table. At times of high tide in the ocean the tide in the ground-water body is still rising toward the high-tide limit shown, and the landward slope is even more extreme than is shown. The lagoonward slope of the high-tide water

table near the center of the island probably results from the ground-water in the high permeability, oceanward part of the island acting itself like the sea in controlling the discharge of the ground-water from the low-permeability, lagoonward part of the island. This behavior suggests a rather sharp discontinuity in the permeability near the center of the island.

As a result of the lower head and greater tidal fluctuation in the oceanward part of the island than in the lagoonward part, the water at the top of the lens is freshest in the lagoonward part of the island, as shown by the dashed line in diagram C which represents the salinity of samples drawn nearly simultaneously from the several wells across the wide part of the island and plotted on a logarithmic scale. The water in well S contained 8 ppm. chlorides, the same concentration as in the original rainwater, and an amount astonishingly low to anyone accustomed to the range in salinities to be found at far greater distances from the sea in the Ghyben-Herzberg lenses of volcanic islands like Hawaii. Water of 250 ppm. chlorides or less could be found within 70 feet of the lagoon shore but not closer than 750 feet from the ocean shore, and water of 1000 ppm. chlorides within 60 feet of the lagoon shore but not closer than 400 feet of the ocean shore. The salinity at the center of the narrow part of the island at the same time was 5500 ppm. as shown in diagram G, indicating the very great importance of the width of the island on the minimum salinity in the Ghyben-Herzberg lens.

The permeability of the near-surface sediments may be estimated from the hydraulics of the shallow wells and from the characteristics of the material, that of the zone occupied by the Ghyben-Herzberg lens may be estimated from the gradients of the water table, and that of the much deeper

zone affected by tidal flow from the tidal lag and damping. The theories linking permeability with these various measurable effects are, unfortunately, poorly worked out, but the rough approximations possible provide some very useful results. The water-table gradients on the two sides of Ine Island indicate an effective permeability ten times or more greater in the zone occupied by the Ghyben-Herzberg lens on the ocean side than on the lagoon side. The permeability coefficients computed for this zone are much greater than those expected in the kinds of sediments found near the water-table, indicating that the reef platform must be a permeability discontinuity below which the permeability is greater than above. The tidal effects indicate that the high permeability continues to a depth greater than that of the Ghyben-Herzberg lens.

These observations, with a number of scattered observations of tidal fluctuation, salinity, and hardness of water not fully worked up yet, indicate that on the wide parts of the islands of Arno Atoll, and probably on wide atoll islands with a similar climate generally, there is a well developed Ghyben-Herzberg lens with a maximum head of about a foot above mean sea level containing fresh water in its upper part. The highest head and freshest water is to be found toward the side of the island under which the average permeability is lowest, which on Ine and Arno at least, and probably very commonly, is the lagoon side. Toward the ocean side the lower head and a greater tidal fluctuation result in greater mixing of the fresh water with the underlying salt water.

Seasonal changes in ground-water

The field observations on Ine were all made during the rainy season in the Marshalls. The heads measured should, therefore, be expected to be

near the maximum to be found during the year, and the salinities measured, therefore, near the minimum. It seems certain that the patterns of head and salinity differences over the width of an island will not differ significantly at any season from that noted, but the amount of decrease in head and of increase in salinity cannot at present be predicted. Monthly measurements of head in a key well are being maintained through a year by the scribe of Ine, so that considerably more information will be available on this point. The data received so far will not be listed here, because they have not yet been corrected for tidal effects and are useless until so corrected.

Native reports indicate that the salt content at the freshest wells on Ine and Bikarij rises enough to be noticeable but not enough to make domestic use of the water impossible.

Utilization of ground-water

The Marshallese draw directly only a small quantity of ground-water. There are no wells in the densely populated part of Ine Village, and the whole water supply there comes from rain catchment. In the more rural areas of both Ine and Arno there are a number of dug wells used almost entirely to supply water for washing clothes. Even where there are wells, the water used for other purposes is rain water. In view of the probable ease of biological contamination of the ground water under such a low, previous terrain, the failure to use much ground water for drinking is probably fortunate. Two of these wells sunk in comparatively high ground were lined with blocks of beach rock. Most were sunk in low places and lined with oil drums with the ends cut out, two oil drums, one on top of another, being used in some. Oil drum wells were seen also on Bikarij by Squires. None of the wells extend more than a couple of feet into the water.

Besides the wells used for wash water there are a number of pits excavated to a foot or two below the water table for use in retting coconut husks. The husks of copra nuts are merely piled in these pits, covered with leaves and trash, and allowed to decompose for a few months, after which the fibers are easily separated for use in making cordage. There is apparently no important salinity control on the retting process, some of the retting being done in pits excavated in the beaches or merely in piles covered with rocks on the beaches. The retting pits in the interior of the islands are apparently located there merely to be convenient to the source of nuts.

The small direct draft of ground-water is no indication of the overall importance of the water that seeps into the ground. As has already been discussed, the water in the unsaturated part of the soil is probably primarily responsible for supporting the heavy vegetation of wet atolls like Arno, but some of the plants are wholly or partly dependent on ground-water from the saturated zone.

Conscious use is made of ground-water in taro culture by the Marshallese. The wet-land forms of taro will grow only in soils saturated with water, and also, it is believed in Hawaii, only where the water is in movement. With no surface streams, the Marshallese have been able to meet the requirements by excavating pits from the surface of the ground 5 or 6 feet or more deep, penetrating the water-table. Taro is grown in organic muck, accumulated by rotting vegetation in these pits. The surface of the muck is generally at about mean water-table, so that water stands in the pits about half the time. The tidal fluctuation of the water-table apparently induces sufficient movement of the water. The area

occupied by taro pits on Ine Island corresponds to the distribution of the freshest ground-water in the lens, that containing 20 ppm. or less of chlorides at the time of sampling. The taro pits on Arno Island occupy a corresponding position, undoubtedly because of the same control. Taro is known in Hawaii to be rather intolerant of salt.

Ground-water apparently plays an additional important part in sustaining breadfruit trees. Breadfruit is not generally regarded as a phreatophyte (plant utilizing ground-water from below the water-table) and on high islands it is clearly not a phreatophyte. However, the distribution of productive breadfruit trees corresponds so closely with the pattern of salinity of the ground water, that some ground-water control seems certainly effectively. It is possible that the control is exercised only during the dry season when vadose water (that held in the unsaturated soil above the water-table) is inadequate to maintain growth, or itself reflects the salinity of the underlying ground water due to capillary rise. In general, the breadfruit trees are limited to a zone including the taro pit zone and extending beyond to a position corresponding to perhaps 200 to 400 ppm. chloride content in the underlying water at the time of sampling. There are a few breadfruit trees growing on Ine Island seaward of this limit, and a few on Arno that probably are also. None of these seaward trees are as large as many of the trees in the center and lagoonward parts of the islands, and it is noted by the Marshallese that they fail to bear or are at best poor bearers. There are no breadfruit trees on narrow parts of the islands. It should be remembered that the limits of a few tens of parts per million chlorides for taro and a few hundreds for breadfruit are wet-season limits. Undoubtedly the dry-season limits representing the real control are considerable higher.

The distribution of settlements and roads, close to the lagoon shore on nearly all of the islands of Arno Atoll, is probably very closely the result of the breadfruit and taro distribution.

Banana and papaya trees show distributions similar to that of taro, but more limited, probably as a result of limiting plantings close to settlements. No other economically important plants seem to be limited by the availability of fresh ground-water.

APPENDIX

Rainfall measurements on Arno Atoll

1950

	July								
	July			August			Sept.	Oct.	Nov.
day	Ine	Arno	Bikarij	Ine	Arno	Bikarij	Ine	Ine	Ine
1				0.50	-	-	0.44	0.54	0.77
2				1.60	1.30	-	1.17	tr	0.07
3				2.52	0.91	-	0.11	0.50	0.40
4				0.58	tr	-	?	0.51	0.39
5				0.00	0.81	-	0.82	0.55	4.56
6				0.57	0.17	-	2.40	1.25	0.45
7				tr	0.35	-	2.10	0.05	0.01
8				0.27	0.09	-	0.55	1.90	tr
9				0.37	2.26	-	1.66	0.24	0.03
10				0.66	0.21	-	0.34	1.17	0.64
11	0.07			0.10	0.18	-	0.89	0.87	0.48
12	0.35			0.91	0.93	-	0.27	tr	0.00
13	0.32			0.30	0.02	-	0.01	0.00	0.00
14	0.17		0.30	1.26	tr	-	0.02	0.00	0.00
15	0.03		0.23	1.21	0.68	-	1.16	0.14	tr
16	0.23		0.11	0.81		-	0.31	0.47	0.00
17	0.43		0.92	0.06		-	0.17	0.00	0.31
18	1.77		-	0.80		-	0.50	0.02	0.08
19	1.24		-	0.27		-	2.77	0.08	0.23
20	0.77		-	0.12		-	0.23	1.10	0.61
21	1.01		-	0.31		-	0.57	0.54	0.25
22	tr		-	0.03		-	0.59	0.09	0.00
23	tr	0.07	-	0.18		-	0.07	0.61	0.00
24	0.39	0.78	-	0.22		-	0.01	2.07	0.12
25	1.36	0.98	-	0.87		-	0.01	0.44	1.88
26	2.42	1.24	-	0.27		-	0.48	0.10	0.49
27	0.47	0.41	-	0.19		-	0.57	0.02	0.54
28	0.50	1.81	-	0.09		-	tr	2.11	0.03
29	0.00	0.66	-	0.55		-	0.00	0.61	0.14
30	0.00	-	-	4.14		-	0.14	0.91	0.00
31	0.03	-	-	0.59		overflowing		0.64	
Total	11.56[a] 17.10[b]	6.05[a]	1.56[a]	20.35	7.91[a]		18.36	17.53	12.49
Mean	0.55			0.66			0.61	0.57	0.42

tr Trace
- Not read. Rainfall included in succeeding reading.
? No record. May be incorporated in succeeding days' catch.
a Incomplete.
b Estimate based on partial record.

Bench Marks at Ine Village

Bench mark 1:

The top of head of galvanized spike driven into north side of coconut palm tree about one foot above ground. Tree is nearest to ocean on southeast side of trail leading to beach from point on main trail about 75 feet northwest of northwesternmost houses of Ine Village, and about 450 feet northwest of main trail intersection at church.

Elevation: 8.71 feet above mean sea level at Ocean.

Bench mark 2:

A small cowrie shell filled with cement and set into top of unused concrete foundation post on south corner of concrete platform around house on north corner at trail intersection at church.

Elevation: 8.27 feet above mean sea level at Ocean.

Bench mark 3:

A circle chiseled in beach sandstone on lagoon beach at foot of trail leading lagoonward from church.

Elevation: 4.39 feet above mean sea level at Ocean.

Bench mark 4:

A circle chiseled on edge of east corner of concrete cistern, 30 feet northwest of trail from church to lagoon a point 125 feet from intersection at church.

Elevation: 6.74 feet above mean sea level at Ocean.

Bench mark 5:

A circle chiseled in south corner of concrete foundation of northwest concrete post at entrance to Ine Council House.

Elevation: 8.80 feet above mean sea level at Ocean.

Bench mark 6:

A circle chiseled in northwest side of concrete sill around Iroij Well, about 140 feet south of main trail at point 75 feet southeast of Council House.

Elevation: 8.14 feet above mean sea level at Ocean.

Bench marks established July 1950. Mean low water elevations and reduction to mean sea level at ocean computed by U. S. Coast and Geodetic Survey.

Tidal data for Ine Island

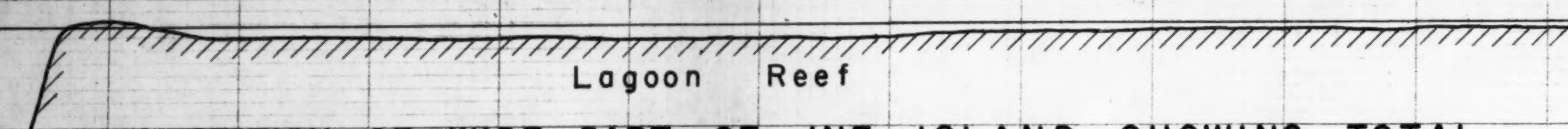
All elevations referred to mean sea level in ocean.

	At ocean	At lagoon
Mean high water	1.90	1.93
Half tide level	0.00	-0.02
Mean sea level	0.00	----
Mean low water	-1.90	-1.97
Mean low water springs	-2.75	-2.82

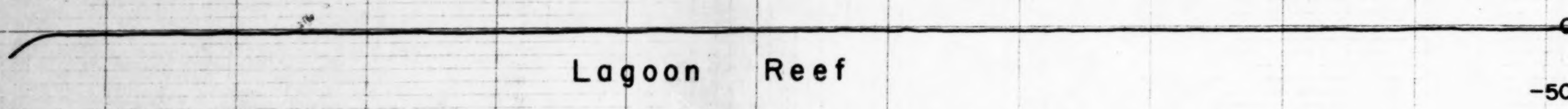
Mean low water elevations and reduction to mean sea level at ocean computed by U. S. Coast and Geodetic Survey.

N.

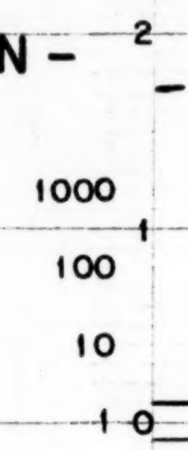
A. CROSS SECTION OF WIDE PART OF INE ISLAND SHOWING SHALLOW GEOLOGIC AND HYDROLOGIC CONDITIONS. VERTICAL EXAGGERATION 10X.



B. CROSS SECTION OF WIDE PART OF INE ISLAND SHOWING TOTAL DEPTH OF GHYBEN-HERZBERG LENS. TRUE SCALE.

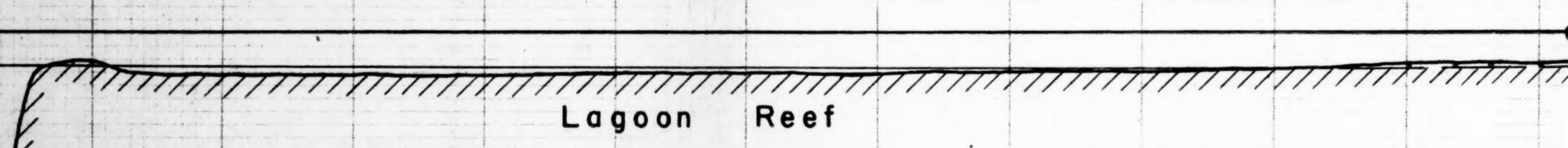


C. GRAPH OF HEAD OF AND SALINITY IN UPPER PART OF GHYBEN-HERZBERG LENS IN WIDE PART OF INE ISLAND

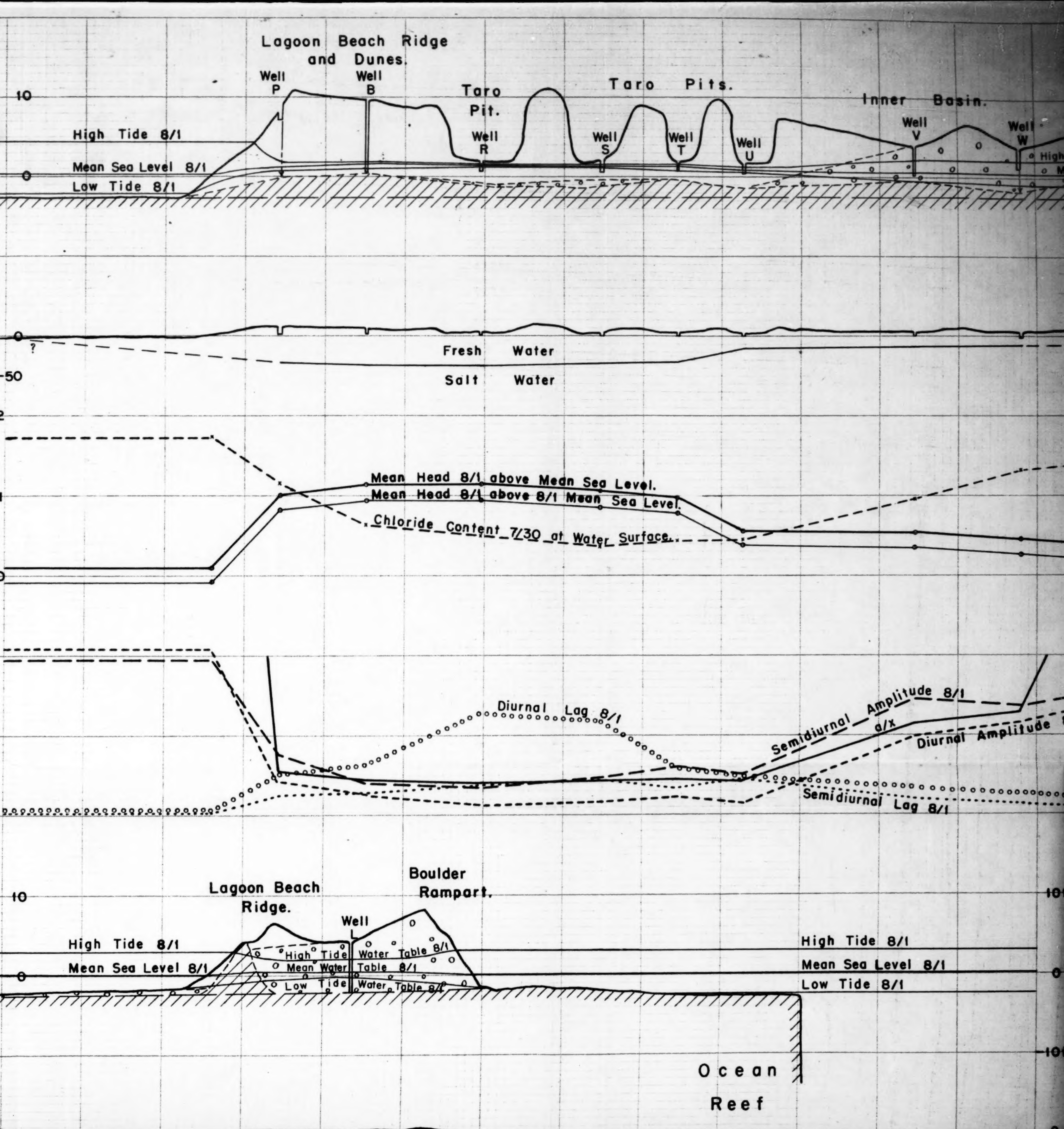


D. GRAPH OF TIDAL FLUCTUATION IN GHYBEN-HERZBERG LENS IN WIDE PART OF INE ISLAND.

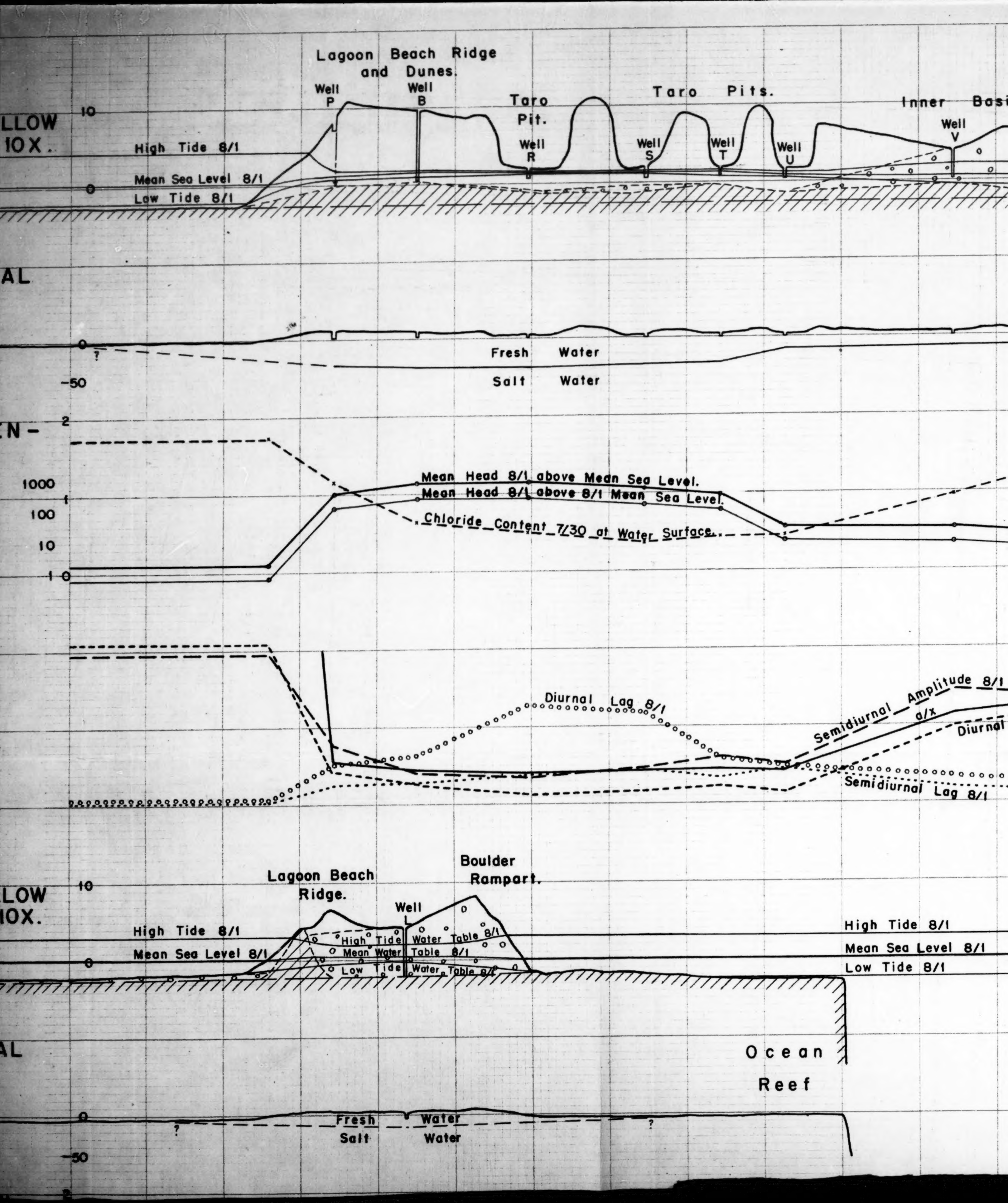
E. CROSS SECTION OF NARROW PART OF INE ISLAND SHOWING SHALLOW GEOLOGIC AND HYDROLOGIC CONDITIONS. VERTICAL EXAGGERATION 10X.



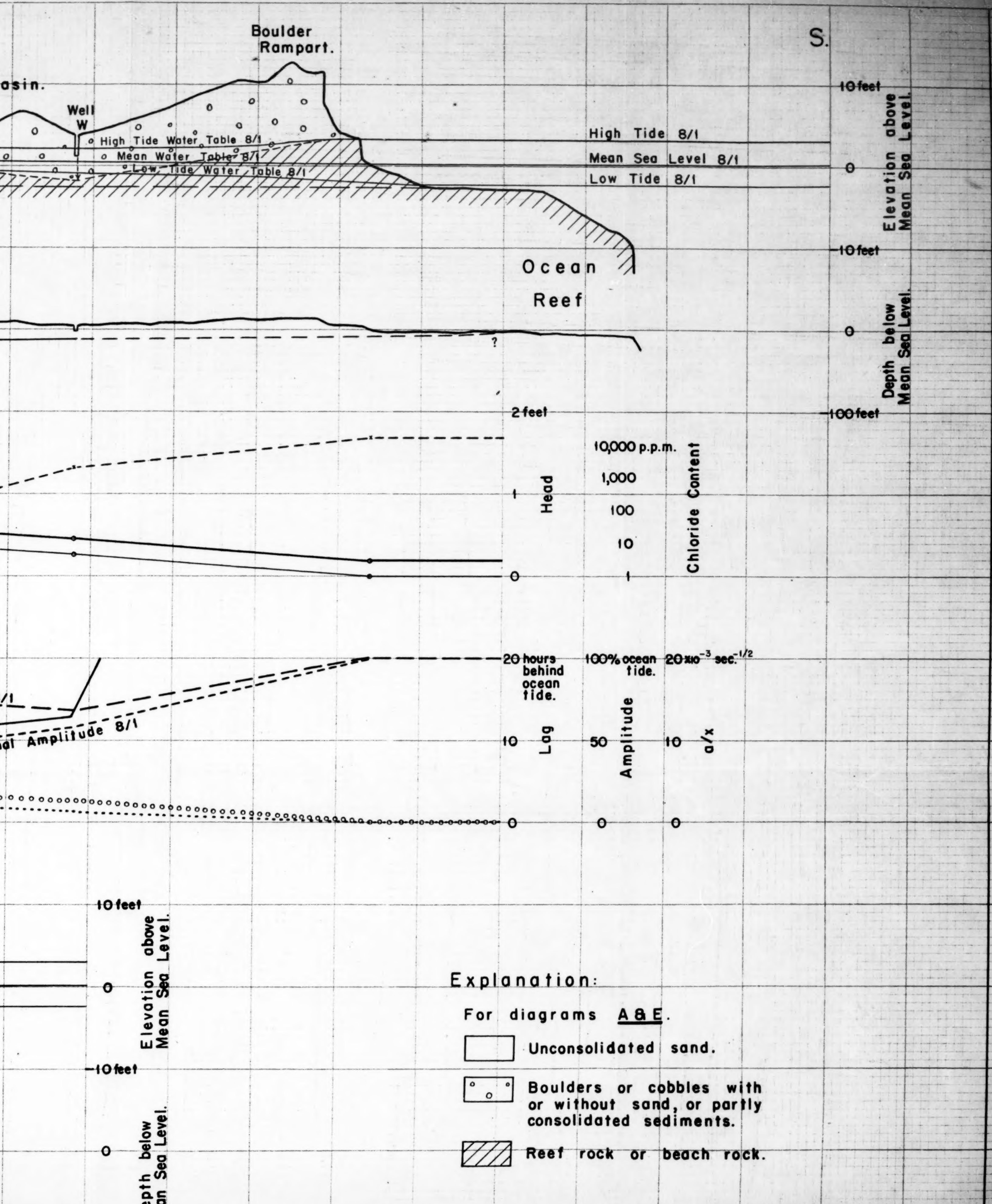
F. CROSS SECTION OF NARROW PART OF INE ISLAND SHOWING TOTAL DEPTH OF GHYBEN-HERZBERG LENS. TRUE SCALE.



Lagoon Beach Ridge and Dunes.
Well P
Well B
Taro Pit.
Taro Pits.
Inner Basin.
Well R
Well S
Well T
Well U
Well V
Well W
10
0
High Tide 8/1
Mean Sea Level 8/1
Low Tide 8/1
Fresh Water
Salt Water
-50
Mean Head 8/1 above Mean Sea Level.
Mean Head 8/1 above 8/1 Mean Sea Level.
Chloride Content 7/30 at Water Surface.
Diurnal Lag 8/1
Semidiurnal Amplitude 8/1
a/x
Diurnal Amplitude
Semidiurnal Lag 8/1
Lagoon Beach Ridge.
Boulder Rampart.
Well L
High Tide Water Table 8/1
Mean Water Table 8/1
Low Tide Water Table 8/1
Ocean Reef

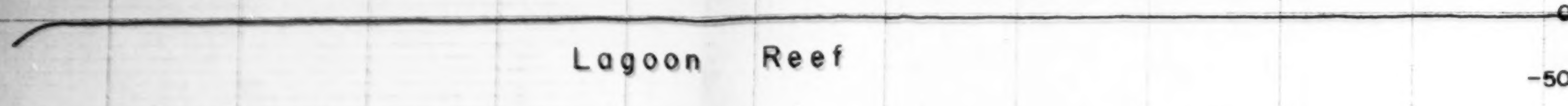


LLOW
10X.
Lagoon Beach Ridge
and Dunes.
Well
P
Well
B
Taro
Pit.
Well
R
Taro Pits.
Well
S
Well
T
Well
U
Inner Basi
Well
V
10
High Tide 8/1
Mean Sea Level 8/1
0
Low Tide 8/1
AL
0
?
Fresh Water
Salt Water
-50
EN-
2
1000
1
100
10
1 0
Mean Head 8/1 above Mean Sea Level.
Mean Head 8/1 above 8/1 Mean Sea Level.
Chloride Content 7/30 at Water Surface.
Diurnal Lag 8/1
Semidiurnal Amplitude 8/1
a/x
Diurnal
Semidiurnal Lag 8/1
Boulder
Rampart.
Lagoon Beach
Ridge.
10
LOW
10X.
Well
L
High Tide 8/1
Mean Sea Level 8/1
0
High Tide Water Table 8/1
Mean Water Table 8/1
Low Tide Water Table 8/1
High Tide 8/1
Mean Sea Level 8/1
Low Tide 8/1
AL
Ocean
Reef
0
?
Fresh Water
Salt Water
?
-50



Boulder
Rampart.
S.
asin.
Well
W
High Tide Water Table 8/1
Mean Water Table 8/1
Low Tide Water Table 8/1
High Tide 8/1
Mean Sea Level 8/1
Low Tide 8/1
10 feet
0
-10 feet
Elevation above
Mean Sea Level.
Ocean
Reef
?
0
Depth below
Mean Sea Level.
-100 feet
2 feet
10,000 p.p.m.
1,000
100
10
1
1
0
Head
Chloride Content
20 hours
behind
ocean
tide.
100% ocean
tide.
20x10^-3 sec.^-1/2
al Amplitude 8/1
10
Lag
50
Amplitude
10
a/x
0
0
0
10 feet
0
-10 feet
Elevation above
Mean Sea Level.
0
Depth below
Mean Sea Level.
Explanation:
For diagrams A & E.
Unconsolidated sand.
Boulders or cobbles with
or without sand, or partly
consolidated sediments.
Reef rock or beach rock.

B. CROSS SECTION OF WIDE PART OF INE ISLAND SHOWING TOTAL DEPTH OF GHYBEN-HERZBERG LENS. TRUE SCALE.

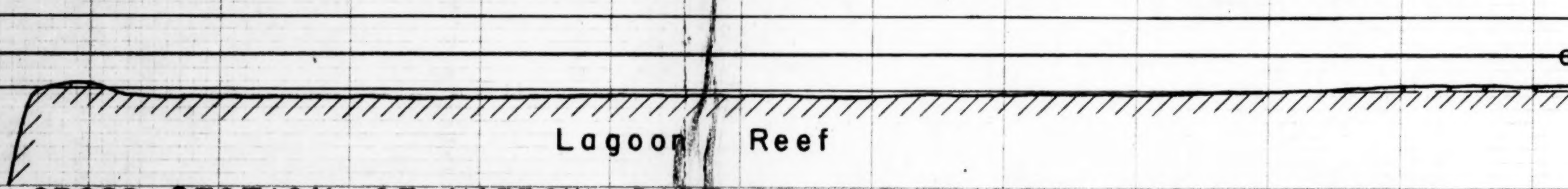


C. GRAPH OF HEAD OF AND SALINITY IN UPPER PART OF GHYBEN-HERZBERG LENS IN WIDE PART OF INE ISLAND

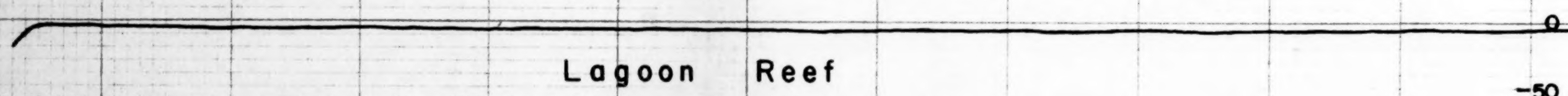
2
1000
100
10
1 0

D. GRAPH OF TIDAL FLUCTUATION IN GHYBEN-HERZBERG LENS IN WIDE PART OF INE ISLAND.

E. CROSS SECTION OF NARROW PART OF INE ISLAND SHOWING SHALLOW GEOLOGIC AND HYDROLOGIC CONDITIONS. VERTICAL EXAGGERATION 10X.



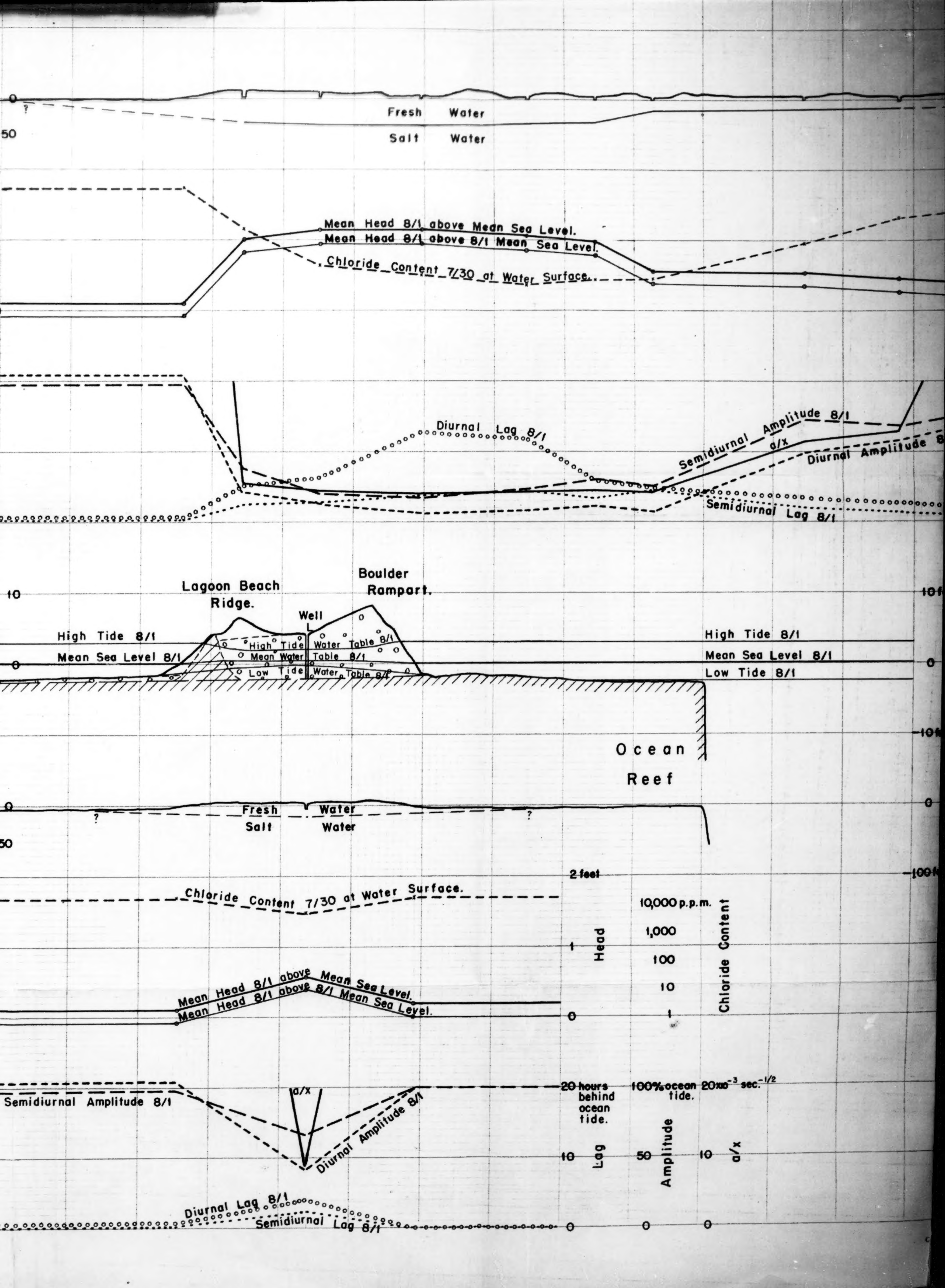
F. CROSS SECTION OF NARROW PART OF INE ISLAND SHOWING TOTAL DEPTH OF GHYBEN-HERZBERG LENS. TRUE SCALE.



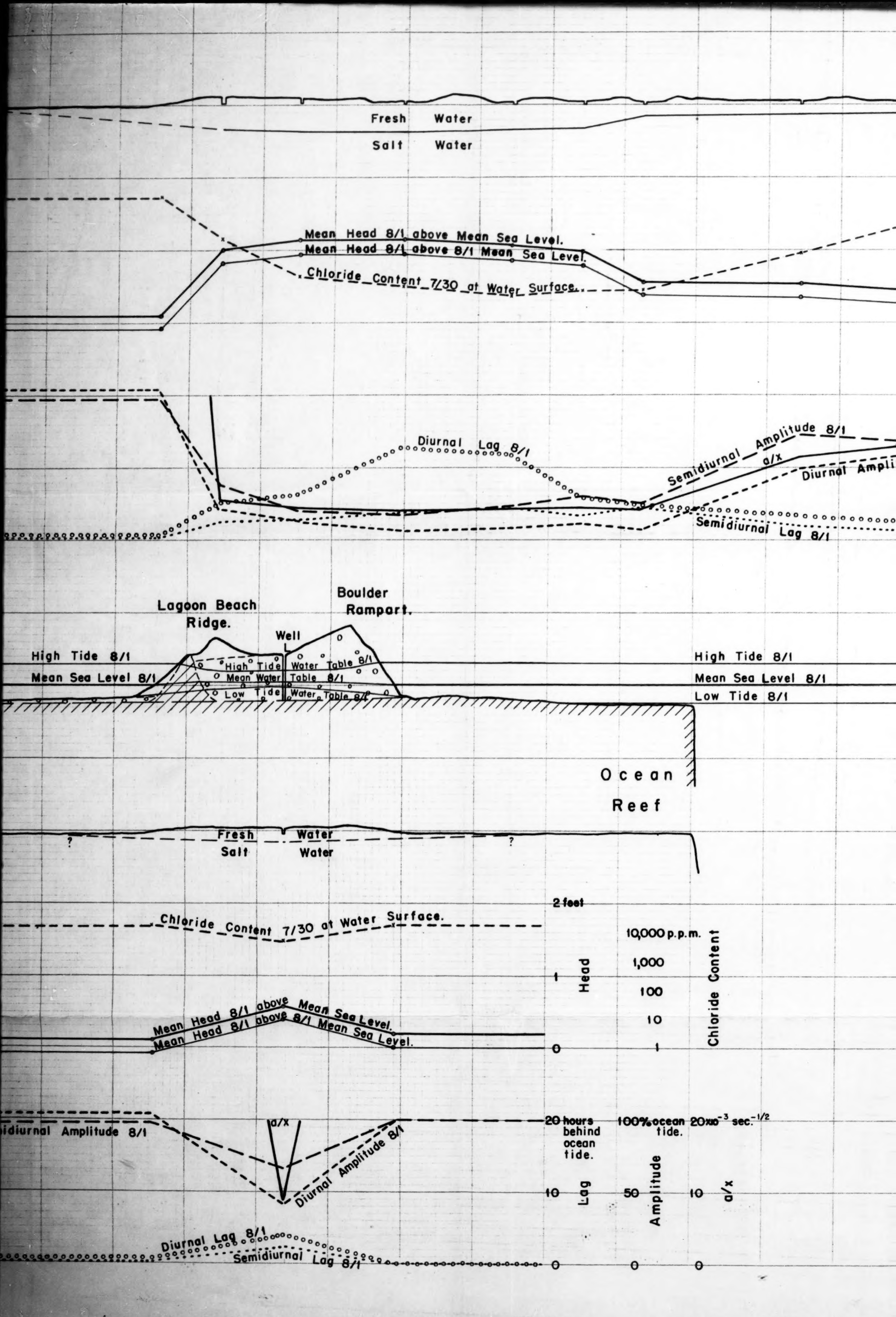
G. GRAPH OF HEAD OF AND SALINITY IN UPPER PART OF GHYBEN-HERZBERG LENS IN NARROW PART OF INE ISLAND.

2
1000
100
10
1 0

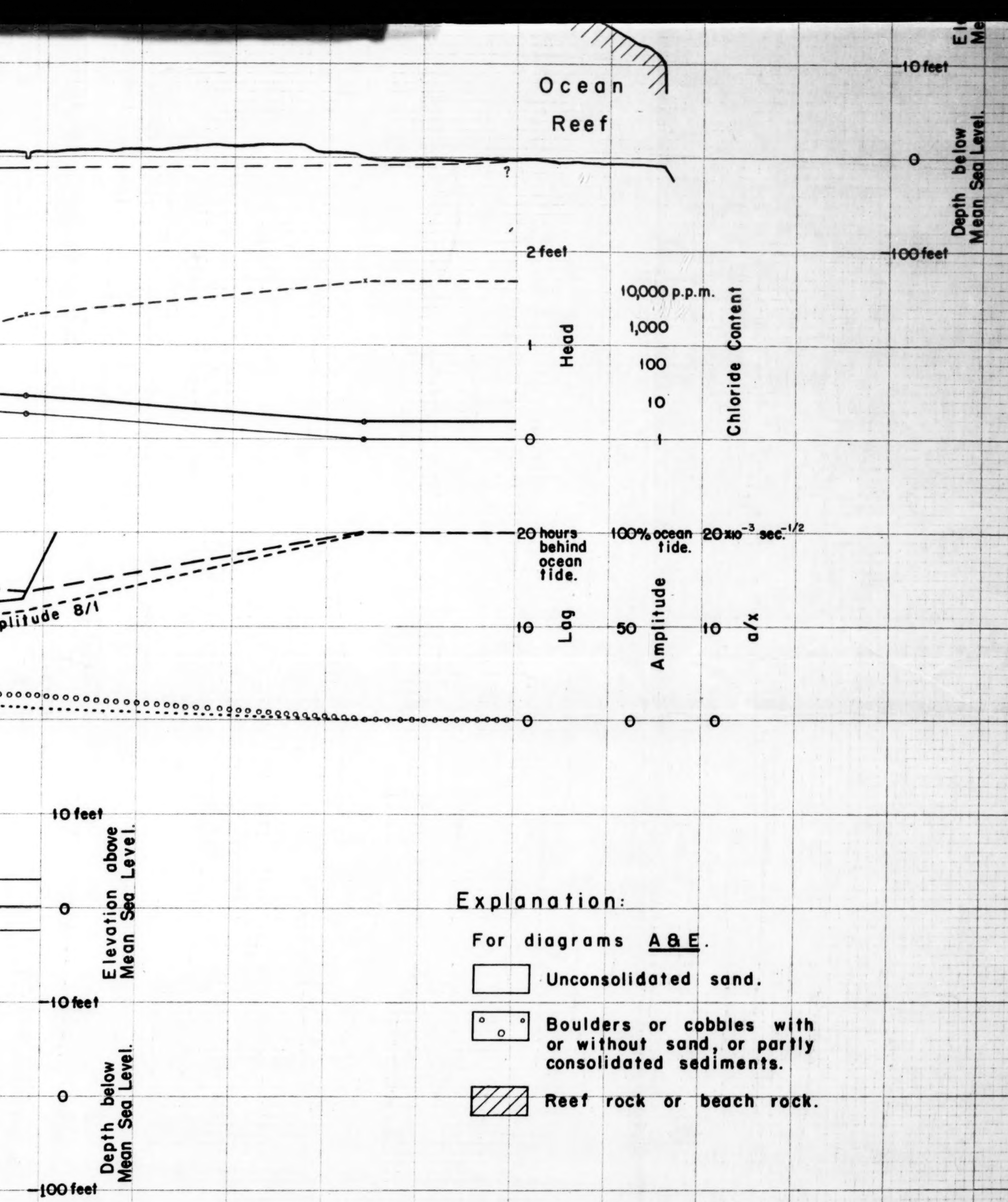
H. GRAPH OF TIDAL FLUCTUATION IN GHYBEN-HERZBERG LENS IN NARROW PART OF INE ISLAND.



Fresh Water
Salt Water
Mean Head 8/1 above Mean Sea Level.
Mean Head 8/1 above 8/1 Mean Sea Level.
Chloride Content 7/30 at Water Surface.
Diurnal Lag 8/1
Semidiurnal Amplitude 8/1
a/x
Diurnal Amplitude 8/1
Semidiurnal Lag 8/1
Lagoon Beach Ridge.
Boulder Rampart.
Well
High Tide 8/1
Mean Sea Level 8/1
Low Tide 8/1
High Tide Water Table 8/1
Mean Water Table 8/1
Low Tide Water Table 8/1
Ocean
Reef
Fresh Water
Salt Water
Chloride Content 7/30 at Water Surface.
Mean Head 8/1 above Mean Sea Level.
Mean Head 8/1 above 8/1 Mean Sea Level.
2 feet
1
0
Head
10,000 p.p.m.
1,000
100
10
1
Chloride Content
Semidiurnal Amplitude 8/1
a/x
Diurnal Amplitude 8/1
20 hours behind ocean tide.
100% ocean tide.
20x10^-3 sec.^-1/2
10
Lag
50
Amplitude
10
a/x
Diurnal Lag 8/1
Semidiurnal Lag 8/1
0
0
0
10
50
0
50
10ft
0
-10ft
0
-100ft



Fresh Water
Salt Water
Mean Head 8/1 above Mean Sea Level.
Mean Head 8/1 above 8/1 Mean Sea Level.
Chloride Content 7/30 at Water Surface.
Diurnal Lag 8/1
Semidiurnal Amplitude 8/1
a/x
Diurnal Ampli
Semidiurnal Lag 8/1
Lagoon Beach Ridge.
Boulder Rampart.
Well
High Tide 8/1
Mean Sea Level 8/1
High Tide Water Table 8/1
Mean Water Table 8/1
Low Tide Water Table 8/1
High Tide 8/1
Mean Sea Level 8/1
Low Tide 8/1
Ocean Reef
Fresh Water
Salt Water
2 feet
Chloride Content 7/30 at Water Surface.
10,000 p.p.m.
1,000
1
Head
100
Chloride Content
10
Mean Head 8/1 above Mean Sea Level.
Mean Head 8/1 above 8/1 Mean Sea Level.
0
1
idiurnal Amplitude 8/1
a/x
20 hours behind ocean tide.
100% ocean tide.
20x10^-3 sec.^-1/2
Diurnal Amplitude 8/1
10
Lag
50
Amplitude
10
a/x
Diurnal Lag 8/1
Semidiurnal Lag 8/1
0
0
0



PROFILES AND GROUND-WATER GRAPHS OF TWO SECTIONS ACROSS INE ISLAND, ARNO ATOLL, MARSHALL ISLANDS.